

Fabrication and Performance of Constellation-X Hard X-ray Telescope Prototype Optics Using Segmented Glass

C. J. Hailey^a, F. E. Christensen^b, T. Decker^c, W. W. Craig^c, F. A. Harrison^d, J. E. Koglin^a, R. Petre^e and W. W. Zhang^e

^aColumbia University

^bDanish Space Research Institute

^cLawrence Livermore National Laboratory

^dCalTech

^eNASA Goddard Space Flight Center



Segmented glass optics represent one approach to the Con-X HXT

- Conic approximation to Wolter geometry
- Shells built out of small glass segments (shell = full figure of revolution, segment = ind. glass piece
- 6 azimuthal sections per shell (cf. SXT: 12 sections/shell)
- Each azimuthal section has 4 segments
- 24 segments per shell
- Mass requirement: ~0.6 mm glass
- Mass goal: ~ 0.2 -0.3 mm glass

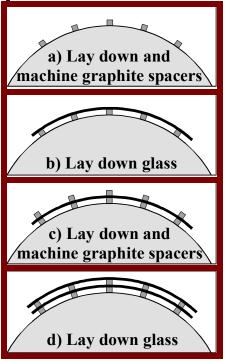


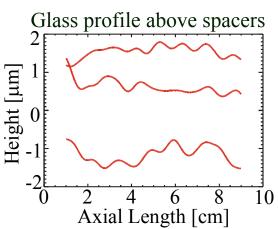
Error Correcting Monolithic Assembly and Alignment (EMAAL)____

■ Each spacer layer (upper & lower) is individually machined to the precise radius and angle:

- > Assembly errors do not stack up
- $\triangleright \sim 8$ " assembly error contribution
- X-ray mirror segments are constrained to spacers with epoxy:
 - \triangleright near net shape shells (~40"HPD),
 - ➤ replica shells for <~ 30" HPD









The errors in the assembly process are understood

Error Budget Summary

- Calibration of relative error in spacer angle measurements: 3"
- Error in spacer radius measurement: <1"
- Spacer position error: 2"-6" (zero error if optic is spun)
- Machined spacer figure: 5"
- ⇒ Total assembly error ~8"

		HPD [arcs		
Tolera		Radius		Description
[inch]	[um]	40	120	Distance between the considerable in
0.002000	50.8	0.1	0.3	Distance between the angular Heidenheins
0.000100	2.5	3.0	3.0	Radius uniformity of calibration mandrel used for the zero
				angle calibration
		3.0	3.0	Calibration error of optical axis angle (error may be
				minimized by finding new focal length)
				Heidenhain Angle measurement: alignment of the mandrel
0.000015	0.4	0.4	0.4	optical axis angle for each shell
0.000005	0.1	0.1	0.4	,
0.000005	0.1	0.1 0.5		Accuracy of each of the angular Heidenheins
		0.5	0.5	Relative error in angle measurement
0.000010	0.3	0.0	0.0	Accuracy of each of the two radial Heidenheins
0.000010	2.5	0.0		Calibration of each of the two radial Heidenheins
0.020000	508.0	0.1		Azimuthal alignment of each of the two radial Heidenheins
0.020000	254.0	0.1		Axial alignment of the upper radial Heidenhein
0.010000	254.0	0.1		Axial alignment of the lower radial Heidenhein
0.010000	234.0	0.2		Total error in radial measurement
		0.3	0.0	Total error in radial measurement
0.000010	0.3	0.0	0.0	Error in clocking of spindle
0.002000	50.8	0.0		Play in wagon wheel pinning
				Dlay in Stronghacks in aligning the spacer wirt the
0.030000	762.0	2.4	0.8	Imandrel in the azimuthal direction
	76.2		0.0	Average azimuthal error in wagon wheel snoke guides at
0.003000		0.0		end of wagon wheels
0.015000	381.0	3.7	12	Twist tolerance of each spacer shoe
				Relative alignment of wagon wheel spoke guides at end of
0.005000	127.0	0.2	0.1	wagon wheels
			1.9	Error in positioning the graphite spacers (e.g., spacer
		5.8		twist and azimuthal alignment)
				, , , , , , , , , , , , , , , , , , ,
0.000000	7.0	0.0	0.3	Mean radial position of all 25 machined graphite spacers
0.000300	7.6	0.3	0.3	w.r.t. goal for upper and lower layers
0.000500	40.7	0.4	0.4	Variation in radial positions of all 25 machined graphite
0.000500	12.7	0.4	0.4	spacers for upper and lower layers
0.000025	0.6	1.3	1.3	Error due to tool wear per 20 cm spacer
0.000050	1.3	2.0	3.3	Average monotonic spacer height variation divided by the
0.000050		3.3		fraction of the spacer overwhich this variation occurs
		5.4	5.4	Figure error due to spacer machining
				Ţ.
		8.5	6.5	Total Error

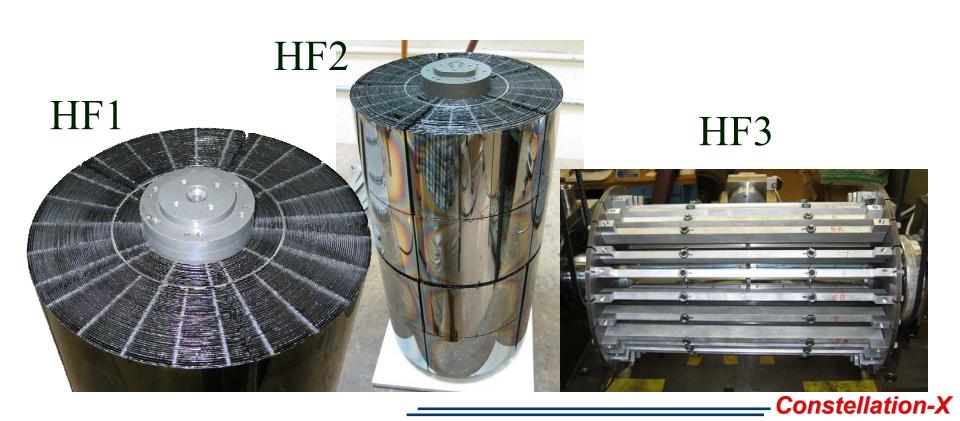




Ability to build flight optics with EMAAL has been demonstrated by HEFT project

- Repeatability in dismounting/remounting
- Fast Assembly one layer per day with 1 tech
- 2 telescopes complete and a 3rd near completion

(~3500+ segments of glass mounted)





The EMAAL mounting approach viability has been demonstrated in shake tests

■ Prototype optic tested in all three axes to the Delta IV qualification level vibration spectrum with no damage to the glass (lowest natural frequency of the glass between supports is ~700 Hz).





Current and planned improvements will complete the upgrades envisioned for HXT fabrication

- Narrow spacers to improve throughput (in process)
- Spin optics during machining to provide radial bias on spacers (in process)
- Automated spacer machining to parabolic and hyperbolic curves for true Wolter-I geometry (demonstrated)
- qualify new epoxies for glass mounting (begin Dec.)
- fix overhang on glass and tighten gap between segments to improve throughput (in process)

- Constellation-X

Two prototypes were constructed using complementary variants of segmented glass approach

Con-X0

Constellatio

- tGlass (=thermally-slumped glass) prototype
- Slump glass into concave mandrel with near net figure
- No replication because X-ray reflecting surface never touches mandrel
- Use for R&D and backup to eGlass at select radii

best performance ~30-40"

Con-X1

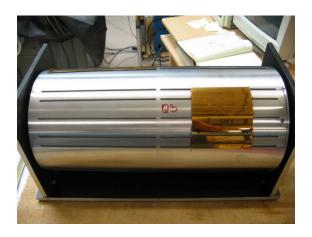
- eGlass (=epoxy-replicated glass)
- Slump glass onto convex mandrel polished to get good large scale figure (but lose good reflecting surface of glass and add midwave ripple)
- Replicate glass on multilayer/epoxy-coated mandrel to recover good X-ray surface and remove mid-wave ripple

obtain << 30" (goal)



Con-X0 and Con-X1 used conical approximation to Wolter I geometry

- 10 cm axial segment per parabola or hyperbola
- Quintant azimuthal geometry with 5 spacers
- 200 and 300 μm glass thickness (Con-X0), 300 μm (Con-X1)
- Focal length: 6.0 m (Con-X0), 4.69 m (Con-X1)



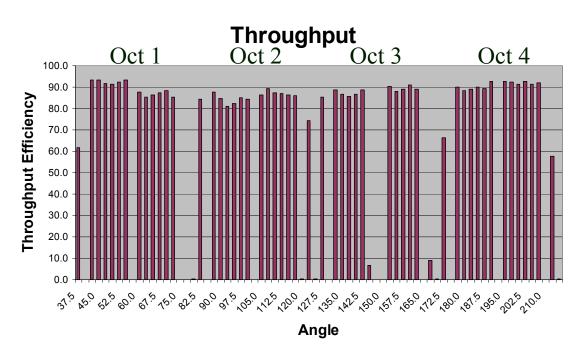


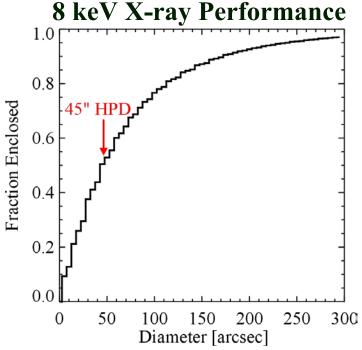
Con-X0 prototype exceeded angular resolution requirement with good throughput

- 16 segments of thermally-formed glass mounted in 4 octant sections.
- Total 8 keV X-ray performance: 45"
- Throughput: 87% (with losses mainly attributed to self shadowing)

CX1 Glass specs

- Schott AF45
- 300 µm thick
- 40 degrees
- 10 cm long
- 80 mm radius





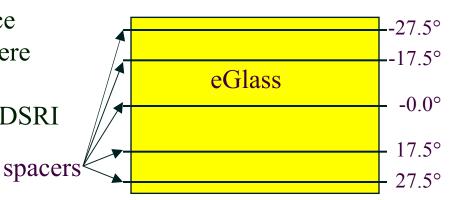
Constellation-X



CX1 Prototype Overview

- The basic telescope design is a conicapproximation Wolter I telescope with the following parameters:
 - Upper and lower shell lengths: 200 mm
 - Focal length: 4693 mm
 - Upper shell radius: 107.1 mm
 - Lower shell radius: 104.8 mm
 - Conic angle of upper shell: 5.6 mrad
- Epoxy replicated glass (eGlass) with dimensions [10 cm long x 60° arc] was mounted on 5 spacers at -27.5°, -17.5°, 0°, 17.5°, 27.5°.
- Two segments were mounted in a 2-bounce configuration, and the other 5 segments were mounted in a single bounce configuration.
- 8 keV X-ray metrology was performed at DSRI

X-ray	y Perfo	ormance
Quad	HPD	S/N
Q1	46"	B469ps (u)
		B507ps (1)
Q2a	55"	B002-25s
Q2b	86"	B467ps
Q3u	45"	S628sb
Q4c	33"	S468pb
Q4d	53"	B470ps



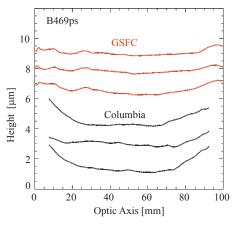
Constellation-X

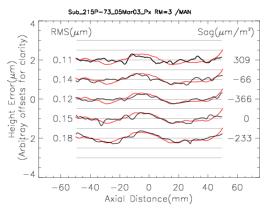
Replication process produces eGlass whose performance on all length scales matches mandrel

 eGlass in Con-X1 suffered large scale figure distortions near edges generated during separation from mandrel due to overly thick epoxy

Constellation

- Short and mid-length scale distortions were removed by replication
- Average performance predicted from laser scans and interferometry for Con-X1 was ~45", 30" for best eGlass segments – this is all figure dominated



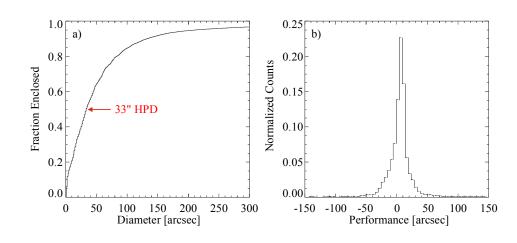


eGlass segments show performance exceeding HXT goal where figure distortion from replication is minimal

- Pencil beam scan of total surface of best eGlass segment = 33" (HPD, 2-bounce) at 8 keV
- ~80% of that area (away from edges where replica distortion is substantial) yields 20" (HPD, 2-bounce)

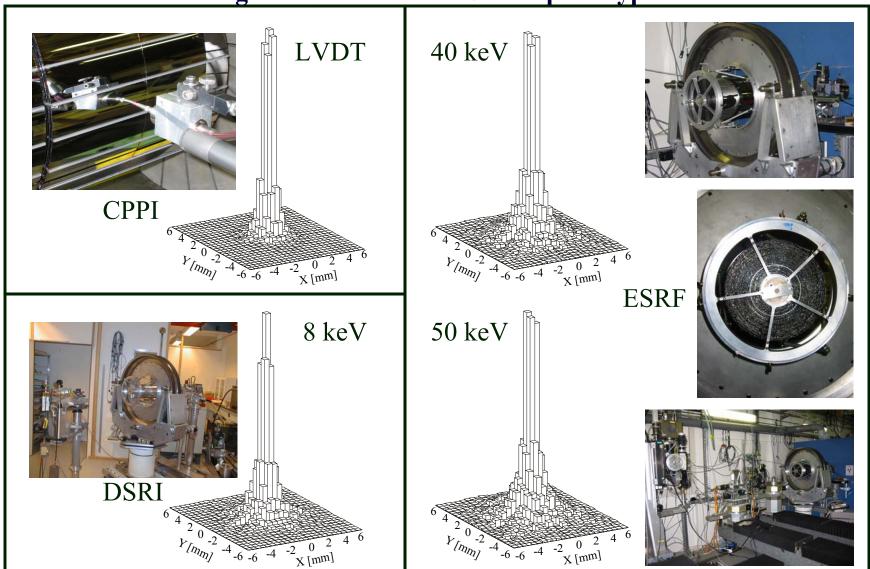
Constellation

- Conclude that with thinner epoxy to suppress large scale figure error that we will exceed the HXT goal of 30"
- Conclude overall contribution of EMAAL to mounted error is < 12"



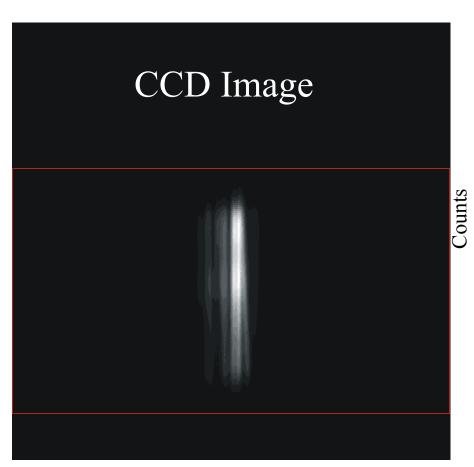


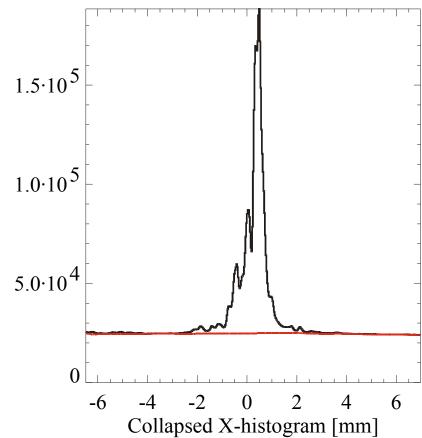
There is good agreement between different measures of angular resolution for Con-X prototypes



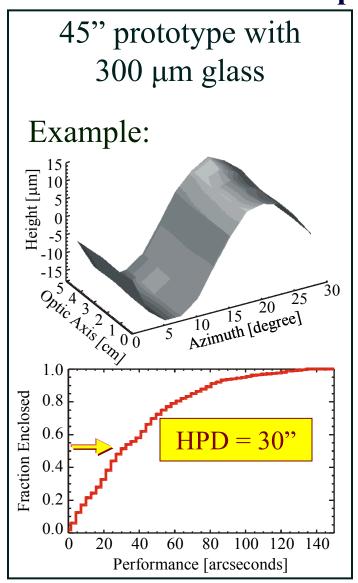


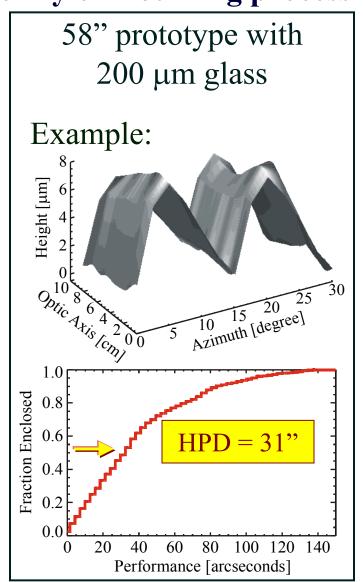
ESRF image of 45" Con-X0 prototype optic





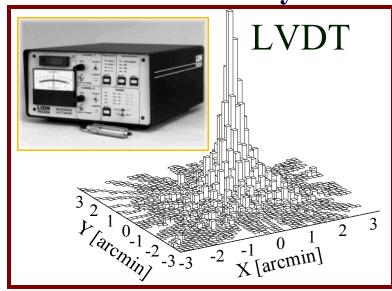
Con-X0 prototype contained some exceptional shells to demonstrate capability of mounting process

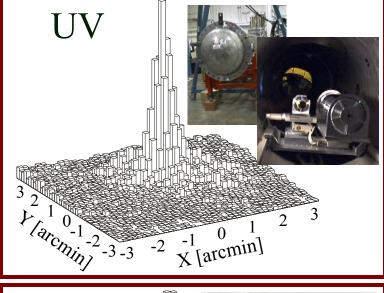


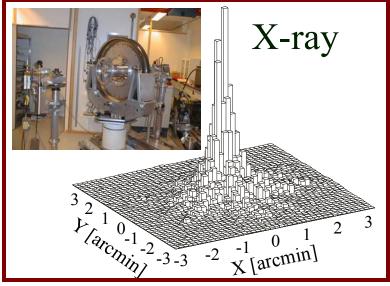


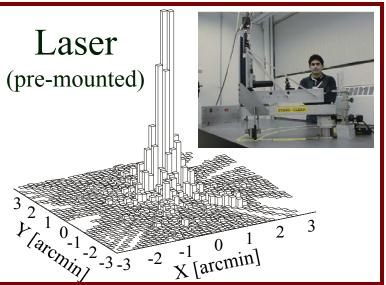


HEFT prototype data demonstrates consistency in various measurements











Simulated stellar images have been acquired in the CASA long beam facility

CASA Long-beam UV facility

- Hollow Cathode Ne Source
- Parabolic mirror creates parallel beam to ~10 arcsec
- Folding mirror used to achieve 6 m focal length
- Optic alignment: < 1 armin
- MCP detector: 3 arcsec resolution







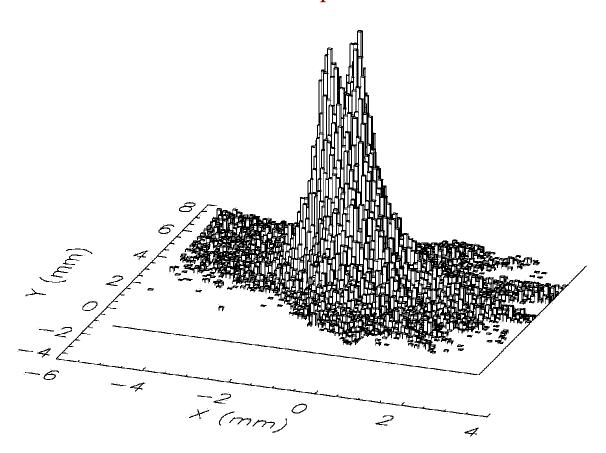


Special thanks to <u>CASA</u> at the University of Colorado in Boulder for technical assistance and the use of their UV Long-beam test facility.



Stellar simulations at CASA using HEFT prototype optic

Hollow Cathode Ne Source Two Pinholes Separated by 30 arcseconds 8 cm² optic





Summary of recent prototype telescope performance

• Best eGlass segment: 33" (20" over 80% of area)

10cm/300 μm/octant

- Best tGlass segment: 26" 5cm/300 μm/octant
- Approximately 70 segments laid (octant) and ~3600 (quintant)

5cm/0.3mm/octant	45"	tGlass (50% accept)
10cm/0.2mm/octant	58"	tGlass (95% accept)
10cm/0.3mm/quintant	60-70"	tGlass (95% accept)
10cm/0.2mm/octant	60"	tGlass (95% accept)
10cm/0.3mm/octant	45"	tGlass (50% accept)
10cm/0.3mm/octant	45"	eGlass

_____ Constellation-X



HXT work will culminate in prototypes with high quality eGlass next year

Near Term:

Mount coated eGlass using good slumping and replication mandrels in small (~10 segment) prototype in next ~2 months and perform X-ray testing at DSRI

Spring/summer next year:

- 3 shells each at approximately 10cm, 20cm, 40+cm diameter
- 10&20cm diameter shells will utilize eGlass with high quality replication and slumping mandrels
- 40+cm diameter shells will be SXT replicas
- Laser reflectometry and interferometry on all shells
- LVDT metrology at CPPI on unreplicated shells and X-ray testing at DSRI on all shells

– Constellation-X



LVDT Surface Metrology

Specifications:

• Range: \pm 50 μ m

• Resolution: 15 nm

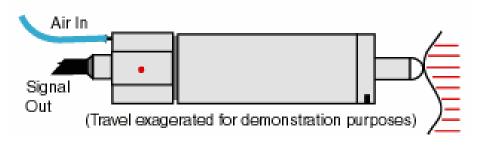
• Noise (P-V): 15 nm

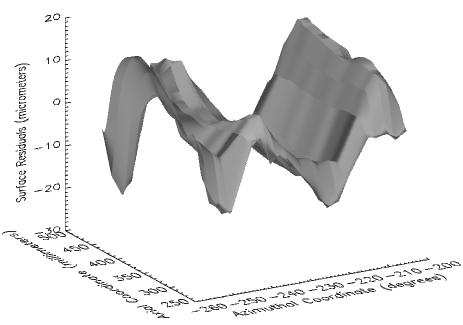
• Linearity: 0.5%

• Probe Force: ~ 1 g

• Signal Output: 5 Hz





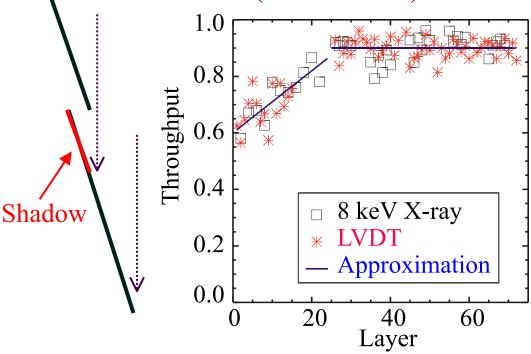


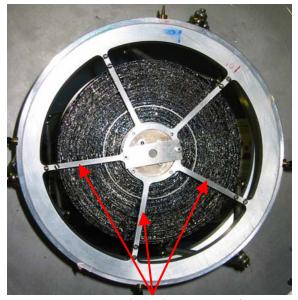
- Air Bearing LVDT Probe produced by Colorado Precision Products, Inc
- LVDT Ultra-high Precision Amplifier produced by Lion Precision



HEFT Throughput

- Shell buckle between spacers can cause shadowing
 - ⇒ Special concern for low graze angle optics
- LVDT and 8 keV throughput measurements agree
 - ⇒ Throughput due to shadowing not contaminants
- Graphite spacers and support structure obscure
 - \Rightarrow 20% (inner shells) \rightarrow 10% (outer shells)



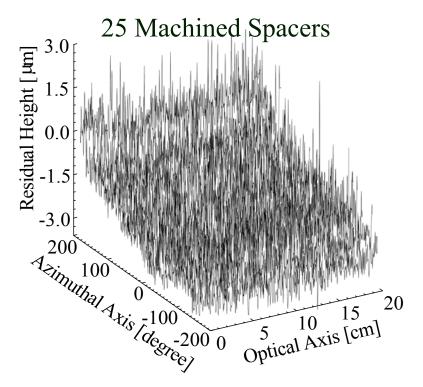


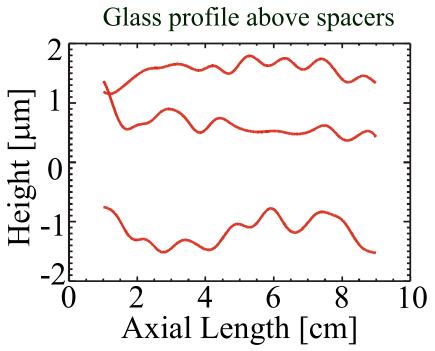
Structural Obscuration



Machining Tolerances are more than adequate for mounting high quality replica glass

Variation in Mean Height: (< 5 arcsec error) μm Spacer Radius Error: (< 0.5 arcsec error) < 15 μm Avg. Spacer Angle Error: arcsec Tool Wear per Spacer: ~ 0.15 (compensation possible) μm Avg. Spacer Roughness: (peak to valley) < 1 μm





X-ray measurements were done at the Danish Space Research Institute

 Triple-axis diffractometer with channel cut monochromator and analyzer crystals

Constellatio

- Measurements done with pencil beam (8 KeV) at 2.5 deg azimuthal intervals and then reconstructed
- Alignment accuracy ~15"
- Estimated error in throughput due to alignment error is <~ few percent







X-ray Facility at DSRI

Scattering at 8 keV (Cu- $K_{\alpha 1}$):

- DSRI triple-axis diffractometer
- Resolution: ~ 5 arcsec FWHM
- Measures figure errors including scattering at < 1800 μm
- Multiple axial measurements performed about optic axis

Specular Reflectivity at 8 keV:

- DSRI double-axis diffractometer
- Resolution: ~ 1 arcmin FWHM
- Measures micro-roughness on lengthscales up to 25 μm





CX0 Prototype Overview

- Both 200 and 300 μ m thick AF45 glass were thermally formed into 80 mm diameter shells, cut to ~ 40° in azimuth extent (55 mm arclength) and both 5 and 10 cm lengths, and multilayer coated.
- The glass segments were mounted to form 20 cm long upper and lower octant sections on top of three graphite spacers spanning 35°.
- The 300 μm glass was chosen from the HEFT inventory of slumped glass. Laser data was used to choose glass expected to have high performance.
- The 200 μm glass was slumped specifically for CX0 by a graduate student. Due to schedule constraints, the slumping parameters for this glass (which differ from the 300 μm glass) were not fully optimized, thus resulting in poorer performing glass than the 300 μm glass.
- Four octant sections of each of the following types of glass were mounted:
 - 1. 200 μ m thick x 5 cm long (32 segments): X-ray HPD = 71"
 - 2. 200 μ m thick x 10 cm long (16 segments): X-ray HPD = 60"
 - 3. 300 μ m thick x 5 cm long (32 segments): X-ray HPD = 76"
 - 4. 300 μ m thick x 10 cm long (16 segments): X-ray HPD = 45"

Constellation-X